Filamentation of high-angle nondiffracting beams and applications to ultrafast laser processing

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Abstract: We report on filamentation of nondiffracting beams and show that the intense light-matter interaction regime achieved on long distances allows for an enhanced control on ultrashort laser deep ablation.

Femtosecond laser micro and nano-processing is a versatile tool which has opened up a broad range of technologies and applications. However, in the particular context of the fabrication of deep channels or trenches in transparent dielectrics like glass, the precise control of the profile of the ablated structure is extremely challenging. Amongst different parameters like incubation or debris ejection, the nonlinear propagation of light in the material and consequent energy deposition are critical.

Strong focusing of Gaussian beams allow for precise energy deposition in a near spherical volume, yielding the formation of nano-voids [1]. In this case, nonlinearities play a minor role. In the contrary, weak focusing conditions increase the interaction length in the material, but the rich filamentation dynamics of femtosecond pulse yield both spatial and temporal distorsions of the pulses. This prevents the precise control of energy deposition along the propagation direction.

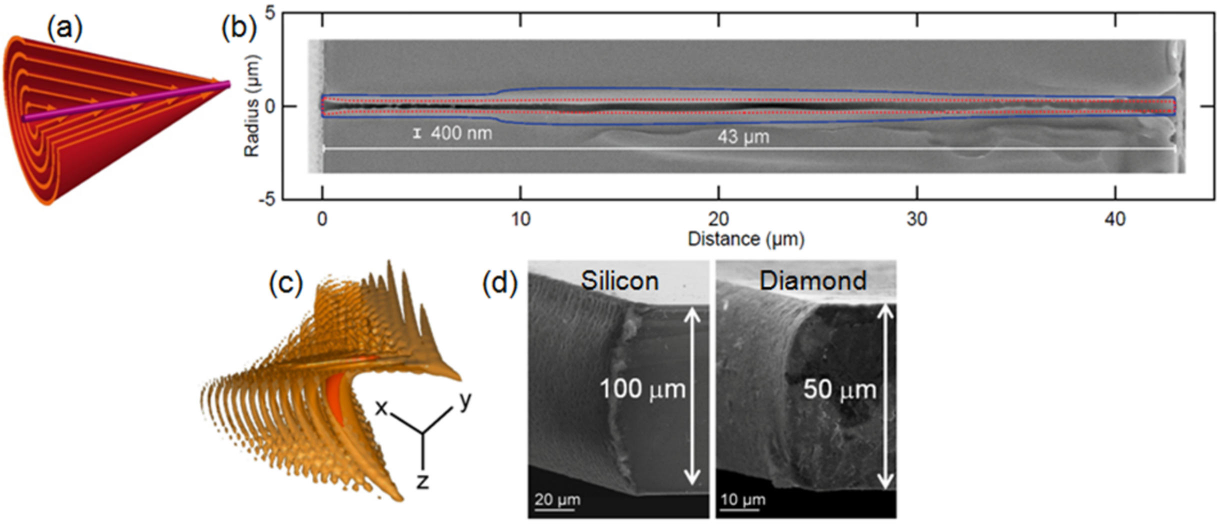

Fig. 1 (a) Conical structure of a Bessel beam generating a uniform dense plasma at its center. (b) Through channel drillled in glass by a single Bessel shot. Blue and red curves show the plasma density iso-contours at the plasma critical density and threshold density for ablation obtained numerically.(c) 3D iso-intensity surfaces at 5%(gold) and 50%(red) of a beam accelerating on a circular trajectory. (d) typical results of edge profiling with circularly accelerating beams.

We have recently developed a novel approach to fabricate controlled high aspect structures using novel Bessel and Airy beams, and this contribution will review our recent work in this field. The key concept behind the use of Bessel and Airy beams in controlled femtosecond fabrication is to control the direction of the incident light field rather than simply shaping the laser intensity pattern in one plane.

With Bessel beams, light propagates along a cone and for sufficiently high conical angles, the nonlinear propagation of femtosecond Bessel filaments is stationary [2,3]. In this regime, we have reported high aspect ratio (100:1) nanochannels drilled in glass using single femtosecond laser shots [4]. Numerical simulations of the nonlinear propagation of femtosecond Bessel pulses allow us to accurately reproduce the experimental results, confirming that the propagation of Bessel filaments during nanochannel drilling is stationary. In addition, we report extremely high plasma densities, even higher than the optical critical density on long propagation distances, as recently confirmed by others [5]. This arises because of the very specific Bessel beam conical structure that allows the pulse to propagate with minimal dynamical effects, thus generating a high aspect ratio cylinder of plasma.

Airy beams and more generally accelerating beams constitute another family of beams that possess quasi-nondiffracting behaviour. Their primary intensity lobe propagates along a curved trajectory that can be arbitrarily shaped [6,7] (Fig. 1(c)). These beams can be described and designed conveniently using the notion of optical caustics and the tools of mathematical catastrophe theory, and we have recently applied this to generate femtosecond beams accelerating on non-paraxial circular trajectories [8]. Significantly, the region of maximal intensity in accelerating beams is adjacent to a region where no light propagates. This has been used for direct curved edge profiling of silicon and diamond (Fig. 1(d)) [9]. In addition, Airy accelerating beams also exhibit stationary propagation as demonstrated by other groups in the paraxial regime [10] and we expect this has important applications in the control of light propagation with high acceleration and applications to nanoprocessing of curved channels.

As a conclusion, our results show that the control of energy deposition in materials with stationary filaments is a key new approach for technological applications and provides access to novel regimes of intense light-matter interaction on long distances and small diameters.

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